Characterization of an Improved, Real-Time MEMS-Based Phase-Shifting Interferometer

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Abstract

We describe and present detailed performance characterizations for an enhanced version of our MEMS-Based Phase-Shifting Interferometer (MBPSI) that achieves 13 times denser motion reconstruction than our original system. We measure the noise level to be ≤±6 nm (λ/110 for a 660 nm laser), and the frequency-resolution to be ≤0.03Hz for 31Hz motion captured at 300Hz. We have successfully tracked a piezo-based actuator, driven with an arbitrary waveform composed of transients ≤10Hz.

Keywords: optical MEMS, Phase-shifting, interferometer, transient motion

1 INTRODUCTION

We have greatly increased the motion reconstruction resolution of our previously reported MEMS-Based Phase Shifting Interferometer (MBPSI) [1], from 23Hz to 300 Hz. This improvement enables the reconstruction of real-time motion with 13-times more samples, resulting in more precise measurements. The improvement is achieved through a combination of higher frame rate of the CMOS imager and newly developed post-processing routines.

Our MBPSI uses a resonating MEMS mirror as the phase-shifting element in conjunction with a strobing laser, as shown in Figure 1 [1]. Synchronizing the strobes with the resonating element eliminates the settling time delay typically found in conventional phase-shifting interferometers, allowing our MBPSI to achieve camera-frame-rate-limited captures similar to digital holographic microscopy [2]. In addition to employing faster imager rates (increase from 92 to 300 Hz), we utilize a simple, yet highly effective new post-processing algorithm described in Figure 2, which quadruples the time resolution of measurements .

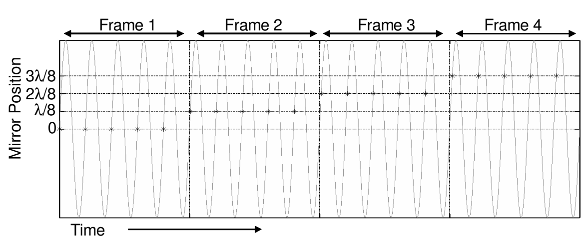

Figure 1. The laser is strobed in sync (denoted by '*') with the resonating MEMS mirror to generate the four distinct phase shifts required for surface reconstruction, within four camera frames.

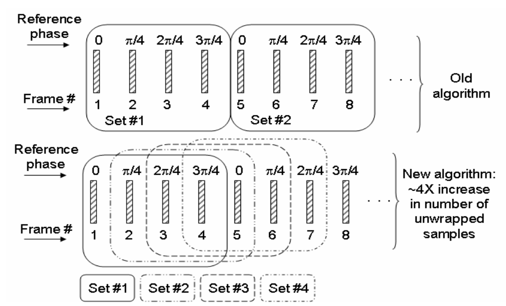

Figure 2. Our new post processing routine divides images into sets for reconstruction by using 3 images from the previous set plus the next image, yielding a 4X increase in the number of reconstructed points.

We have also characterized the capabilities of the system by using a piezo-bending actuator as the test sample. The noise level is ≤±6 nm (λ/110 for a 660 nm laser), and the frequency resolution of the measurement is better than 0.03Hz for tracking 31Hz motions captured at 300Hz. Finally, we have successfully applied our system to reconstruct arbitrary non-periodic motions of a PZT actuator.

2 EXPERIMENT SETUP

We use a modified Twyman-Green configuration interferometer, as shown in Figure 3. The test sample is a mirror mounted on a piezo-driven bending actuator.

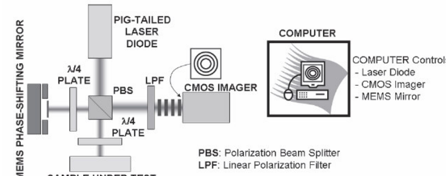

Figure 3. MBPSI experimental setup in Twyman-Green configuration

The image area was set to 160 by 640 pixels, corresponding to a 160 µm by 640 µm mirror surface. The camera gain and brightness were constant for all experiments. The laser-pulse width was set to 1.2µs. The laser-strobes per frame were 12, 8 and 5 for frame-rates of 100, 200, and 300 Hz respectively. Every experiment was conducted within a capture window of 4 seconds. Data were processed using the 4-frame phase-unwrapping algorithm. The position at each point in time was calculated as the mean over the entire imaged area. The motion plots were generated by subtracting the initial position from each of the subsequent positions.

3 RESULTS

3.1 Noise level

The noise level was determined by continuously measuring a static surface over 4 seconds, and analyzing the measured position variations. The histograms of position variations show Gaussian distribution, with standard deviation (σ) of 1.47nm, 2.05 and 2.93nm for 100, 200 and 300 Hz frame rates respectively. For Gaussian distribution, 95% of the values fall within $\pm 2\sigma$ of the mean value, yielding a noise limit of $\leq\pm 6$ nm for the system ($\pm\lambda/110$ for 660nm laser) at 300Hz. Higher frame rates show higher noise levels because the number of laser strobes decreases, resulting in a lower signal-to-noise ratio of the captured images.

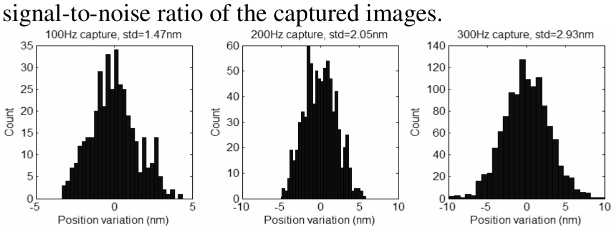

Figure 4. Measured position variation of a static surface over time at different frame rates yields a base noise level of 6nm (2σ) for 300Hz

3.2 Frequency-resolution

To determine the frequency-resolution, the test sample over a ±75nm range with sinusoids at known frequencies. Analysis of the frequency spectrum shows that 31Hz motion can be tracked to within 0.03Hz, as shown in Figure 5.

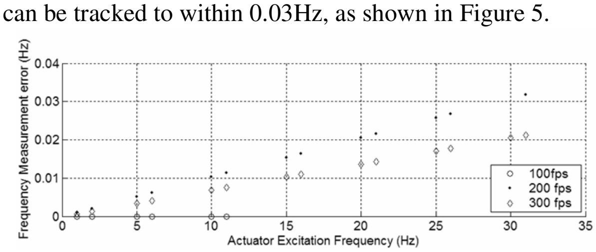

Figure 5. Frequency-resolution of a moving actuator at different capture rates show the expected trend of decreasing accuracy with increasing sample frequency, and increasing accuracy with higher capture rates

3.3 Transient-motion capture

Arbitrary transient motion was emulated by driving the sample with a custom waveform composed of five weighted sinusoids in the range of 1 to 10Hz (listed in Table 1).

Table 1. Frequency and weights of sinusoids used to generate arbitrary driving waveform

	f_1	f_2	f_3	f_4	f_5
Freq.	1 Hz	2 Hz	3 Hz	6 Hz	10 Hz
Weight	$^1/_{16}$	$^1/_{16}$	$^1/_8$	$^1/_4$	$^1/_2$

The reconstructed motion closely matches the expected motion in the time domain, as shown by Figure 6(a). The frequency spectrum, plotted in Figure 6(b), shows that the largest deviation between expected and reconstructed motion, arises from tracking the amplitude of the 10Hz component. The amplitude error is lower when the measurement rate is 200Hz, as expected.

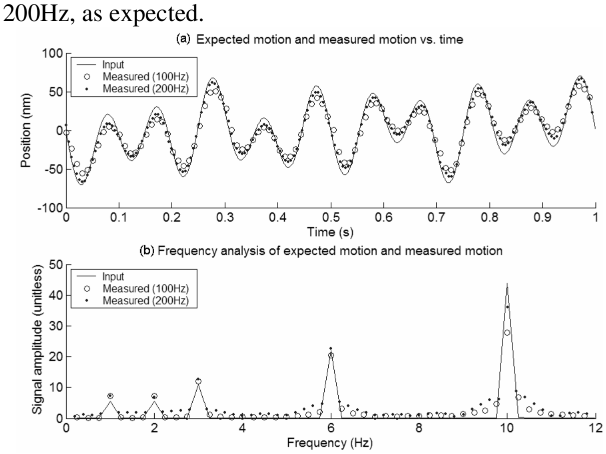

Figure 6. (a) Expected and measured motion (b) Frequency decomposition of expected and measured motion

4 CONCLUSIONS

We have successfully demonstrated and carefully characterized the improved version of our MEMS-Based Phase-Shifting Interferometer for real-time transient phase-shifting interferometry. We obtain a noise level $\leq\pm 6$nm, and frequency-resolution of 0.8Hz for tracking 30Hz motions allowing us to accurately track the real-time motion of a piezo-bending actuator.

REFERENCES

[1] H. Choo, R. Kant, D. Garmire, J. Demmel and R. S. Muller, "Fast, MEMS-Based, Phase-Shifting Interferometer," Proc. of Solid-State Sensors, Actuators, and Microwave Systems, Hilton Head, NC, USA, June 4-8, 2006, pp. 94-95.

[2] Y. Emery, E. Cuche, F. Marquet et. al., “Digital Holographic Microscopy (DHM) for metrology and dynamic characterization of MEMS and MOEMS,” Proceedings of SPIE, April 21, 2006, pp. 205-209.